

BARM: Bi-Angular Rotation Machine as an External Combustion Machine

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Abstract Schapiro (2011) introduced the BARM as an internal combustion machine, and Schapiro (2012) introduced the BARM as an external combustion machine. This article introduces the thermodynamics of an external combustion BARM in the physical approximation (Chap. 3), designed specifically for exploiting thermosolar energy. The economic and political aspects are discussed in Clause 4.3. A comparison between BARM and Stirling machines is the primary focus of this article. The efficiency of both machines as thermosolar energy exploiters is compared under two scenarios: in the first, the Stirling machine has no heat recuperator and the BARM no heat exchanger. In the second scenario, the Stirling machine is equipped with a heat recuperator and the BARM machine with a heat exchanger. That efficiency is dependent on the power flow through the machine has been taken into consideration. The thermodynamic description, that is the modelling of these processes, is a physical approximation valid not only for BARMs, but for all rotational volume displacement machines in similar application, for instance, in Pyatov (2010) and Pyatov and Schapiro (2010).

1 Precursors

BARM is an abbreviation for: Bi-Angular Rotation Machines. The form of the rotational piston's cross-section as an arc-figure with two corners gives the machine its name. The precursors of the BARM have been well known since the 1920s. To date they have been developed and deployed only as compressors.

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Like all rotating piston machines, BARMs, too, run smoothly and quietly and have high power density. They have a cylindrical design which simplifies assembly and reduces the time and energy requirements for production. They are capable of diesel operation in a single section because their smallest residual volume can theoretically be zero and the volume and location of the separate combustion chamber required for internal combustion is completely independent of the trochoidal geometry. Thus, one can generate almost any compression ratio desired with BARMs (Fig. 1).

2 BARM as an Internal Combustion Machine: Short Review

BARMs employ a different trochoidal chamber geometry than the classic Wankel engine. Like all rotary piston machines, power takeoff is achieved via eccentric planetary gearing. The key element here is an innovative, pendular sealing element that seals the piston surface-to-surface with the chamber walls rather than line-to-surface, as in the classic Wankel engine, Schapiro (2011, 2012).

The chamber contour here is not circular but rather a trochoid, an algebraic figure of the 4th order. BARMs are volume displacement machines capable of deployment in all relevant areas. We expect their particular advantages to be evident when employed as environmentally friendly, high performance combustion engines, range extenders for electric vehicles, emergency power generators, compressors, thermosolar and geothermal engines and machines for exploiting high and medium temperature exhaust heat of all kinds. As our thermodynamic analysis demonstrates, employing BARMs enables more efficient energy production and use than is possible with the classic Wankel engine, thereby saving energy. Let's take a look at a comparison between reciprocating piston and BARM engines, both in diesel versions (Fig. 2).

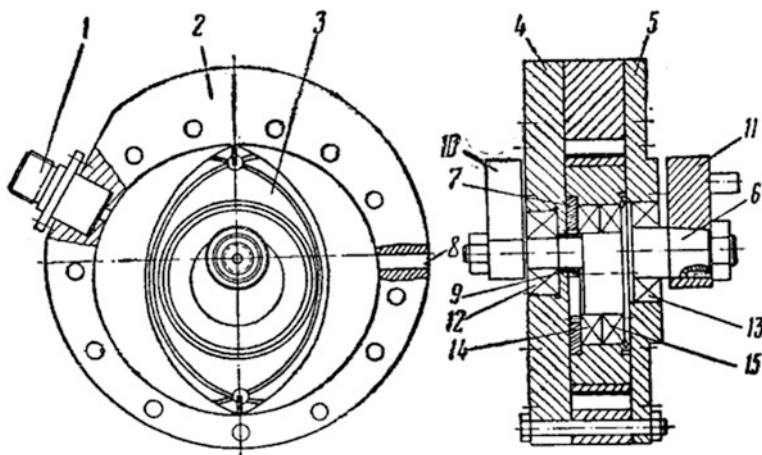


Fig. 1 A compressor developed at N. Zhukovsky State Aerospace University “Kharkiv Aviation Institute” in the 1960s and repeatedly deployed in industry. Cited from Sukhomlinov (1975)

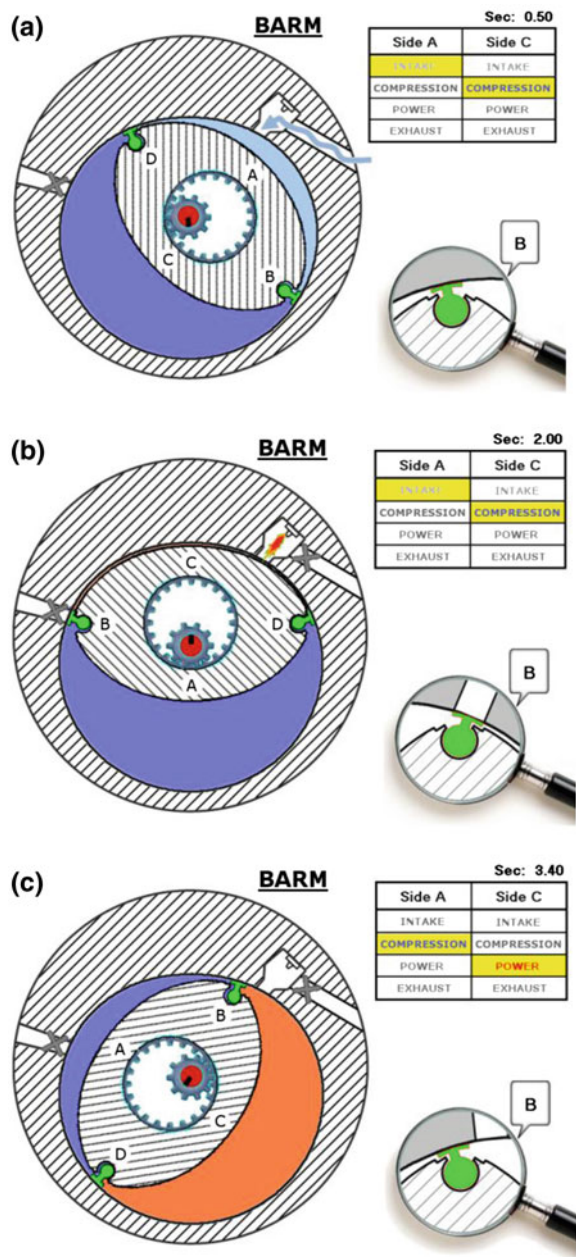


Fig. 2 a–c Schematic BARM as a 4-cycle engine. Each side of the piston works as an independent piston. Thus a single BARM power unit is equivalent to a two-piston reciprocating piston machine. Shown here are sample piston positions. Constructing a BARM with two pistons powering one drive shaft creates an engine equivalent to a four-cylinder reciprocating piston engine. Every BARM cycle in the two-unit combination is a power cycle, continuously transferring torque to the driveshaft

In this simulation, both the reciprocating piston and BARM machines run a diesel process. They have the same working volume, the same cycle start and end pressures, the same cycle length, “burn” the same amount of fuel per cycle and piston side and, of course, deliver the same energy efficiency under these conditions, namely, 56 %.

Under these conditions, the BARM delivers almost twice as much power per cycle compared to the reciprocating piston engine because both sides of its piston work. It is important to note that—seen kinematically—the BARM piston can turn faster by a factor of almost 4 than can the crankshaft of the reciprocating piston machine under otherwise comparable conditions. If this simulation corresponded to reality, an increase in power density by a factor of 8 ($2 \times 4 = 8$) could be theoretically expected. We think that BARM combustion engines will actually have a three to occasionally five times higher power density than reciprocating piston engines with the same working volume. Thus we expect that a BARM engine can achieve equivalent performance and equal exhaust gas quality as a reciprocating piston engine with but 20–30 % of the latter’s size and weight!

Material for the engines as well as energy for production is also conserved because of the high BARM power density. There exist sufficient heat and pressure resistant materials, such as metaloceramics, silicon carbide and other ceramic materials to withstand the high combustion chamber temperatures (Kriegesmann 2005).

In the state diagram Fig. 3a, the blue point passes the orange point and then the orange passes the blue, so they complete each cycle in the same time. The graphic in Fig. 3b shows the lower portion of the time-dependent function of both volume displacements (orange for BARM and blue for reciprocating piston) from the driveshaft and crankshaft angles of rotation for similar working volumes. The graphic in Fig. 3c shows the comparison of the simulated performance over time, blue for the diesel reciprocating piston and orange for the BARM. Performance is negative at certain points because the machines use energy for moving the pistons and compressing the air. Significantly more energy is won; however, because burning releases the stored chemical energy and both engines convert this energy into usable power driving the driveshaft or crankshaft respectively.

BARM combustion engine CO₂ emissions will be in the same range as that of reciprocating engines and significantly less than the Wankel engine’s due to the higher efficiency of BARMs. The problem with NO_x emissions is the same as it is for reciprocating piston engines.

Competing technologies: Both reciprocating piston engines with their efficiency and classic Wankel engines with their power density compete in this arena. BARM and other rotating piston engines offer the same advantages in the 10 kW to 10 MW power range and thus have a competitive advantage in the technology and industrial markets. BARM does not compete with gas turbines since turbines are usually highly effective in power ranges above 10 MW.

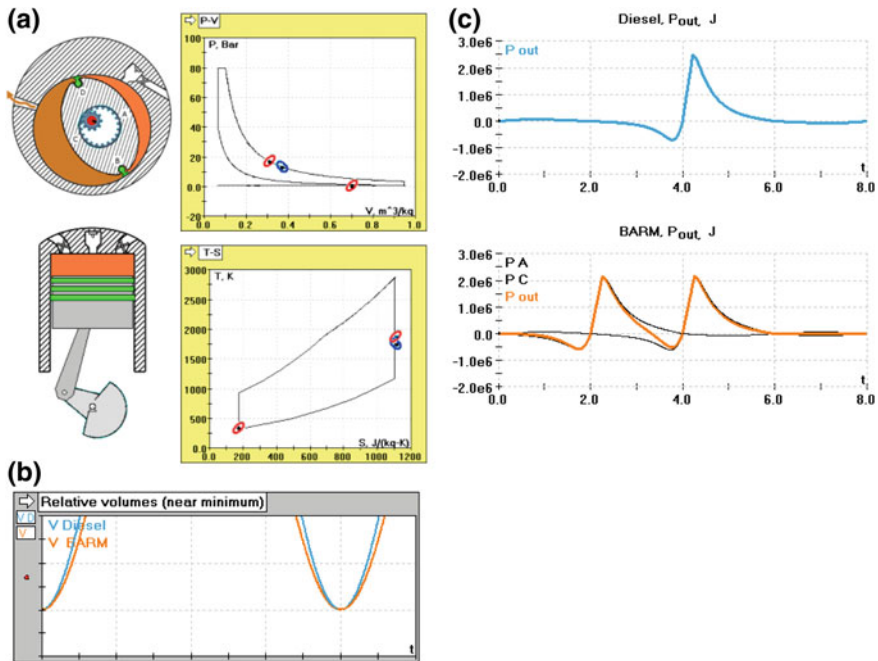


Fig. 3 a–c A thermodynamic simulation approximating non-deformable piston and housing as well as a working medium with no viscosity. The *blue* point and *blue* curves corresponds to the reciprocating machine, and the *red* one to the BARM. The work cycle is on side A of both the BARM and the reciprocating piston. The points in the *red, right-leaning ovals* in the state diagram mark the thermodynamic state on sides A and C of the BARM piston. The concomitant state is marked by the point in the *left-leaning, blue oval* for the reciprocating piston

3 BARM-Utilization as Heat Engines, External Combustion Machine

Heat engines with cyclically regenerative working media, or external combustion machines, do not use chemically stored energy internally to produce mechanical power. They use an externally produced temperature difference, hence, the name external combustion machine. They produce mechanical power by transferring heat from a hot site to a cold site in such a way that part of the heat can produce useful mechanical power. Such machines employ a working medium, usually gaseous, that is cycled back and forth between the heater and the cooler (Fig. 4).

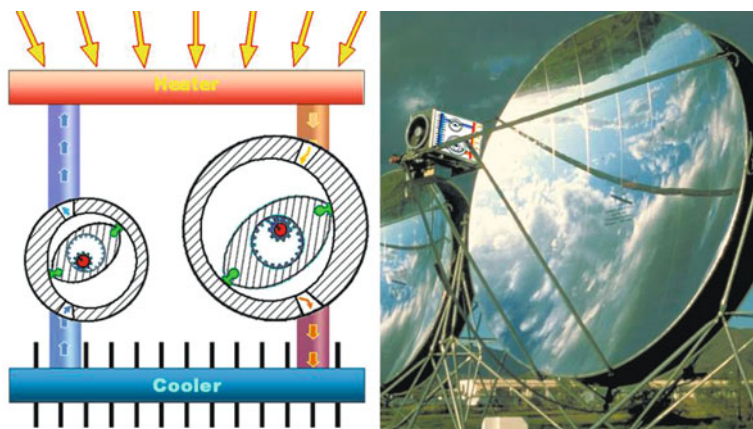


Fig. 4 The larger machine on the sketch's *right* is an expander, that is, a motor. The smaller machine on the *left* is a compressor. The working medium could be helium or another medium. Both machines are laid out such that their power shafts turn at the same speed. Thus both motor and compressor can be mounted on the same shaft which also drives the generator and a cooling fan. With this layout, the machine almost has but a single moving part with a complicated form, namely two pistons, permanently geared to a single power shaft

We wish to use BARMs as heat engines, not only to capture and exploit the waste heat from industry and municipalities but also for power generation using nature's free energy sources, especially thermosolar.

3.1 General Remarks Concerning Heat Utilization

One of the most promising uses of BARM machines is for transforming heat to mechanical power. That is, anywhere there is a heat source available with a working medium between 400 and 1,200 °C of sufficient capacity to deliver between 10 kW and 10 MW of heat energy. This encompasses a wide variety of industrial waste heat sources, such as waste steam and exhaust gases and the burning of flammable waste gases, as well as focused solar heat and thermal output of geothermal sources. Our rough estimate of the total annual potential of all industrial and municipal waste heat is in the range of 1,000,000 GWh, approximately one-fourth of world energy requirements today.

Currently, there exists no technical standard with satisfactory efficiency to utilize the heat available from these sources. The highly efficient turbine technology is advantageous only in the multiple megawatt power range. At present, the best alternative for heat utilization in the low and medium power range is the Stirling engine. Therefore, we wish to compete with the Stirling engine.

3.2 *Stirling and Other Ideal Cyclical Processes*

It is generally well known that no heat engine can surpass the efficiency of a Carnot machine embodying the ideal Carnot cyclical process. It is less well known that a number of other thermodynamic cyclical processes can exhibit the same coefficient of efficiency η as the Carnot process under ideal conditions. Among these are the Stirling cyclical process especially and, under a few specific conditions, the Rankin process with $\eta_{\text{ideal}} = (T_{\text{heater}} - T_{\text{cooler}})/T_{\text{heater}}$. We focus primarily on the Brayton-Joule process. We will show that, as a precursor to our design, it is the best fit to our design for technical and economic reasons. With current technology, the Rankin and Brayton-Joule processes are realized with turbines which exhibit an acceptable efficiency only in the multiple megawatt range. Until now, the Stirling process was the only one employing the principle of volume displacement and implemented with a reciprocating piston engine. The efficiency of an actual Stirling engine depends on how closely the real process can be made to approach the ideal. The same holds true, of course, for the other cyclical processes, this also holds true for our modification of the Brayton-Joule process.

3.3 *BARM Versus Stirling Engine*

The BARM volume displacement heat engine realizes a new cyclical process we developed together. It is most closely related to the Brayton-Joule cyclical process. Even in an ideal representation, the BARM heat engine does not achieve Carnot ideal efficiency. But since when is our world ideal? Only our beloved wives! So, the future for BARM and for the Stirling engine as heat engines depends entirely on the extent to which technical realization can minimize variance from the ideal. In this respect especially, we consider the BARM competitive with the Stirling engine for the following reasons:

- The BARM has a significantly higher power density than the reciprocating piston Stirling engine. Consequently, its compact architecture.
- With distinctly fewer moving parts, the BARM must be not only smaller, lighter and more economical to produce, but also more reliable than the Stirling engine.
- While we expect very similar friction losses in the working chamber and conduits of both engines, we expect notably less friction losses in the power shaft and bearing mechanics.
- And most importantly—under realistic conditions, that is, with a heat regenerator, BARMs will deliver higher efficiency than Stirling engines.

3.4 The Role of the Regenerator and Heat Exchanger, Respectively

The comparison in Fig. 5 was made without employing a regenerator for either engine. The regenerator idea consists of separating the heat path from the mass of the working medium. With the help of a heat exchanger, one can return a portion of the heat remaining after the power phase to the working medium after the cooling phase. Thus the thermodynamic losses due to irreversible cooling can be minimized.

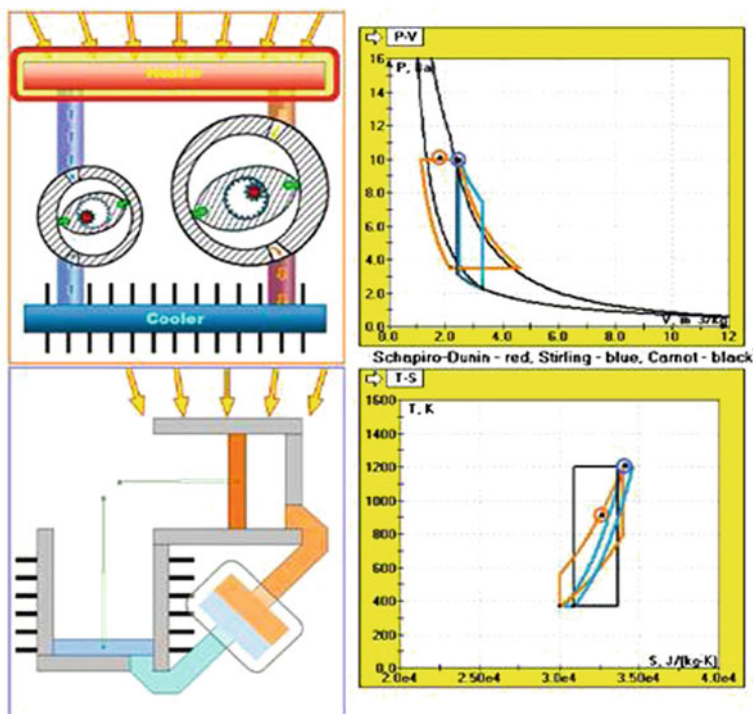


Fig. 5 A thermodynamic comparison between a substantially idealized (although not ideal while without heat regenerator) Stirling engine and an only slightly idealized BARM. The BARM's superior efficiency is obvious. Of course we examined this comparison over the entire relevant power spectrum. The results are not shown here because the comparison really makes sense only when a heat regenerator, that is, a heat exchanger, is incorporated

But the irreversible losses in the Stirling engine seem to be greater than those in the BARM heat engine. That is associated with the typical efficiency of the Stirling engine's heat regenerator, generally in the 60 % range (Fette 2012). The efficiency factor of industrial heat exchangers that can be employed with the BARM is approximately 95 % (Jüttemann 2001). Therefore, we expect that, in reality, BARMs with heat exchangers will outperform today's almost perfected Stirling

engines. The relationship of both machines overall efficiency factors will, of course, depend on the output load.

The comparison of overall efficiency is made under thermodynamically equal conditions. The working medium in both engines is He_2 with a mass of 100 g, the maximum volumes of the working chambers are equal, as are the maximum and minimum temperatures, 1,200 and 400 °K respectively. For the simulation, we assumed an exaggerated efficiency factor of 70 % (blue circlets) for the thermal efficiency of the Stirling engine's heat regenerator and 90 % (red squares) for the BARM's heat exchanger. Losses due to mechanical friction and viscosity of the working medium were not incorporated for either engine.

The ends of the curves in Fig. 6 to the right and left of the graph mark the position where thermodynamic utilization is no longer possible. The Stirling engine's efficiency increases monotonically until reaching its maximum value, at which point the working medium can no longer take up heat and thermodynamic function collapses.

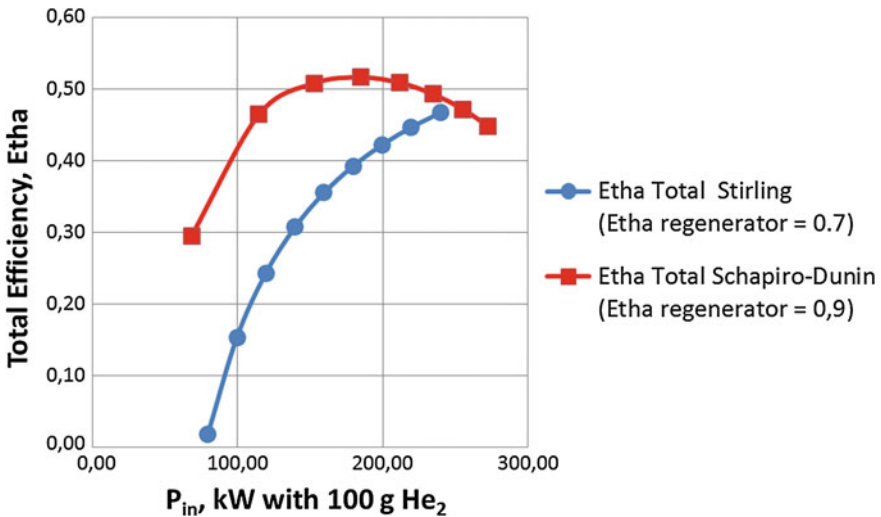


Fig. 6 The computer-simulated total efficiency factor η of the Stirling engine versus BARM, with thermal input P_{in} in kW, an exaggerated efficiency factor of 70 % for the Stirling engine's heat regenerator (blue circlets) and 90 % (red squares) for the BARM's heat exchanger, the same 100 g He_2 as working medium for both engines, a maximum temperature of 1,200 °K and a minimum of 400 °K

The overall efficiency factor of the BARM with a 90 % efficient heat exchanger reaches a maximum of 52 % with an energy input of approximately 180 kW. That is around 12 % more than the idealized Stirling engine's overall efficiency and around 18 % better than the overall efficiency of the best Stirling engine currently in use, namely 34 %. Two demonstration models of the BARM exist currently, but no practically tested prototype.

If there is interest in lower power applications, e.g., for decentralized power supply, one can reduce the mass of the working medium. Thus one could achieve approximately the same overall BARM efficiency with but 1 g He_2 and energy input of 1.8 kW, theoretically resulting in 1 kW energy output. Of particular interest is the BARM's equation of state, resulting in a maximum pressure of 10 bar and a minimum pressure of 3.8 bar. That should result in prodigious reliability and extended service life for the engine. The same holds for the Stirling engine, of course. Thanks to the still valid Boyle & Mariotte law, one can minimize the dimensions of both machines inversely proportional to desired pressure.

Competing Technologies: Stirling engines are one of the technologies competing for thermosolar use and heat recapture. The picture in Fig. 4 shows a dish Stirling engine, part of a thermosolar pilot project by the firm SOLO in Spain. We have pasted in a schematic of our BARM to show the potential. Stirling Energy Systems, a US company, achieved a world-record efficiency for Stirling engines of 31.25 % in 2008. Nonetheless, it was forced to declare bankruptcy in 2011.

3.5 Uses as Thermosolar Power Plants and for Heat Recapture

We believe BARMs can be successful in commercial heat utilization in the medium temperature range, such as industrial waste heat recapture and geothermal power plants. Stirling engines are better than BARMs in the low temperature range. However, there is insufficient commercial potential in this range to warrant great effort in this area, except perhaps as a hobby. We expect a clear victory for BARMs in the high temperature range, particular with thermosolar power plants.

4 Conclusion

After intensive and wide-ranging study, our conclusions are:

4.1 External Combustion Machines, e.g. for Thermosolar Energy Production

- 4.1a. As a trochoidal rotating piston machine, BARM's advantages are higher power density with concomitant smaller dimensions and significantly less weight. BARM's high rotation rate means that its power density is limited only by the rate of temperature increase and the viscosity of the working medium.

- 4.1b. In contrast to the well-know Wankel engine, trochoidal BARMs will have a very long service life. The reasons for this are described in Sect. 4.2b.
- 4.1c. BARMs with heat exchangers are particularly interesting in the high temperature range around 1,000 °C, where they can achieve the same efficiency—slightly more than 40 % (optimistic estimate: up to 45 %)—as other volume displacement engines under realistic conditions.
- 4.1d. The external combustion BARM gains a small efficiency advantage from the fact that, from its starting position, the BARM piston opens the crescent-shaped working volume more slowly than a reciprocating piston (both compared at the point of minimal volume). Compared with other common geometries, this lengthens the isochoric pressure increase phase, thus improving efficiency slightly.
- 4.1e. A further advantage is the BARM's simple construction which, along with the lighter weight, promises lower production costs and longer service life. The expectation that external combustion BARMs will produce only slightly higher efficiency than other volume displacement machines relates to the fact that theory predicts the efficiency factor's dome-shaped dependence on the pressure relationship with a maximum in the range of $P_{\max}/P_{\min}$ from 8 to 10 for the more powerful high temperature version. Thus, the real strength of volume displacement engines, namely their ability to create large pressure differentials, cannot contribute to increasing efficiency in thermosolar applications. Nonetheless, BARMs can contribute significantly to increasing power density as well as lowering production costs.

4.2 Internal Combustion Engines for Motorized Energy Production

As internal combustion engines, BARMs can, in principle, actualize every known cyclical process. The Diesel or Atkinson cycles are especially attractive. We believe that internal combustion BARMs offer the most advantageous combination of high power density, good efficiency, low noise level and affordable production costs.

- 4.2a. High power density is typical of all trochoidal rotating piston engines. High rotation speed is the best known advantage of the Wankel engine with the resulting power density. The same holds true in full measure for BARMs.
- 4.2b. Long service life. The principle difference from the Wankel engine is the long service life of BARMs. The Wankel engine's short service life is not caused, as many believe, by deterioration through wear of the sealing lips. The sealing lips are expendable parts, easily replaced regularly. The short service life results primarily from damage to the interior of the chamber caused by the unavoidable resonance of the sealing lip oscillation due to the high rotation frequency. The fundamental geometric cause of the sealing lip's impact on the chamber wall is due to the inner contours of the Wankel

engine's chamber which has both concave and also convex (or at least not concave) stretches. Strong centrifugal forces act on the sealing lips when they slide off the contour very quickly. These forces change their direction during the transition from a concave to a convex stretch and again from convex to concave. The change of centrifugal force direction, amplified by the resonance, hammers deep grooves into the interior wall of the working chamber. These grooves thus appear as though they had been hacked in with an axe. This damage to the interior chamber wall is the real cause of the Wankel engine's short service life. Mazda's RX Wankel engine set a world record of about 150,000 km equivalents on the test stand. The service life of a good Mercedes or Peugeot reciprocating piston diesel engine exceeds 2,000,000 km in a vehicle. The BARM engine's inner chamber wall is very close to a circle in cross-section, that is, only concave, and the curvature of the chamber changes little by little, only gradually and minimally. Thus, changes of direction or quick changes in the sealing lip's centrifugal force cannot occur and damage to the interior chamber wall à la Wankel is never a problem. Therefore, we expect BARMs to have a long service life, certainly not less than that of the classic reciprocating piston engines.

- 4.2c. We attribute the BARMs good efficiency as volume displacement, internal combustion engines to the fact that their efficiency's dependence both on the temperature differential $\Delta T/T_{\text{Burn}}$ as well as on the pressure ratio $P_{\text{max}}/P_{\text{min}}$ (and also the compression ratio) always increases monotonically. Thus, volume displacement engines can really take advantage of their strength, namely the ability to develop great pressure differentials, to increase efficiency. At a burn temperature of 2,000 °C, exhaust gas temperature of 550 °C and a compression ratio of 24:1, diesel BARMs could theoretically deliver full load efficiency of about 60 %, without considering potential increases via a turbocharger, for example, or other devices. The expected power to weight ratio would be under 1.0 kg/kW (compare: Otto engines 2–5 kg/kW, diesel engines 5–6 kg/kW).
- 4.2d. We attribute the low noise level to the design's lack of piston rods and crankshaft which are a major contributing factor to the noise levels produced by reciprocating piston engines. Further, noise producing tensions in the motor can, for the most part, be compensated for by the centrally symmetric disposition of the working units, as shown, Schapiro (2011).
- 4.2e. We expect affordable production costs due in particular to the increased power density (less material per performance kilowatt) and the resulting power to weight ratio of 0.5–1.0 kg/kW, as well as fewer parts and a production-friendly cylindrical construction, similar to the Wankel engine.
- 4.2f. Because of all these characteristics, we consider BARMs particularly suited for light aircraft engines, low to medium weight helicopters and drones, among others.

4.3 Economic and Political Aspects

BARM provides the potential for a true energy transition both as an internal combustion engine, providing high power density with the same efficiency as reciprocating piston engines, and as an external combustion machine with higher efficiency and power density than Stirling engines. BARM technology can be deployed anywhere, enabling decentralized and diversified energy production between 10 and 30 kW, tailored to the actual needs and sites where it is in fact utilized. This can be realized with the low weight, inexpensive production and small dimensions of BARM engines. If a BARM engine were working on every building and in every industrial facility, one could truly speak of a sustainable and not only seemingly “cost free” energy transition. The costs of a “sustainable” energy transition in the EEG sense tax even successful and productive economies. The German energy management system is not suited for worldwide utilization in any case. BARM technology would be effective worldwide: using BARM engines rather than outdated diesel generators is resource-saving and sustainable energy production. The political potential of BARM technology:

- Conversion of the energy economy. The difference between the economic and political price of energy displays alarming aberrations. On the bourse, a kilowatt hour costs 3.8 cents today. For us, the small end-user, it costs 28.6 cents.
- Avoid the expected financial costs of the transition to supposedly “cost free” energy that already weigh on our entire economy and each individual. These include the costs for disposing of nuclear wastes, disassembled reactors and the construction of new mega conduits for electricity transport.
- Avoid the political costs to be expected with implementation of the mega conduits over the protests of directly affected local residents with a new distribution philosophy.
- Ease the overall political situation by reducing the fear of the centralized omnipotence of the energy concerns and the political impotence of governmental agencies in the energy sector. Instead, build trust and solidarity in the population by granting localities responsibility for their own energy production.
- Prevent the occurrence of extreme worst cases with individually configured energy production facilities for small user entities.

The introduction of a truly new technology such as the BARM technology can induce, finally, desperately needed innovation in the energy economy. BARM enables the conversion of an overpriced, overly complex and thus unmanageable, failure-prone energy production system to a technically easily managed, simple and economical energy production system.

Acknowledgments First and foremost, the authors would like to thank Karl Sittler, Zurich, Switzerland, for his untiring help and support during the entire last decade. We also thank Prof. Yuri Estrin and Dr. Boris Feldmann, Melbourne, Australia, for the manifold consultations in materials science. We give wholehearted thanks to Dr. Andreas Leson, Dresden, Germany, and Dr. Edgar Voelkl, Austin, Texas, USA, for their many years of staunch support. Prof. Lev Britwin

and Dr. Ivan Pyatov, Moscow, Russian Federation, we give great thanks for their continuous support as well as their patient and valuable counsel. Dr. Igor Sedunov, St. Petersburg, Russian Federation, we thank for his continuous attention to our work. To our wives, Hella Schapiro and Galina Dunin, we offer deep and wholehearted thanks that they not only tolerate our work but actively support it as best they can.

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